

A SEYFERT-2-LIKE SPECTRUM IN THE HIGH-MASS X-RAY BINARY MICROQUASAR V4641 SGR

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ABSTRACT

We present an analysis of three archival *Chandra* observations of the black hole V4641 Sgr, performed during a decline into quiescence. The last two observations in the sequence can be modeled with a simple power-law. The first spectrum, however, is remarkably similar to spectra observed in Seyfert-2 active galactic nuclei, which arise through a combination of obscuration and reflection from distant material. This spectrum of V4641 Sgr can be fit extremely well with a model including partial-covering absorption and distant reflection. This model recovers a $\Gamma \simeq 2.0$ power-law incident spectrum, typical of black holes at low Eddington fractions. The implied geometry is plausible in a high-mass X-ray binary like V4641 Sgr, and may be as compelling as explanations invoking Doppler-split line pairs in a jet, and/or unusual Comptonization. We discuss potential implications and means of testing these models.

1. INTRODUCTION

The nature of X-ray emission at low Eddington fractions remains uncertain. It is particularly interesting to explore connections between accretion inflows and jet outflows in X-ray binaries at $L \simeq 10^{-4} L_{\text{Edd}}$, as this regime may provide insights across the mass-scale into the much larger class of low-luminosity active galactic nuclei (LLAGN) which exist at comparably low Eddington fractions. Recent work on V404 Cyg, for instance, has shown that jet production can occur over many orders of magnitude (see e.g. Gallo, Fender, & Pooley 2003).

One particularly well-studied jet-producing X-ray binary is SS 433. SS 433 is unique in that its jets can be resolved in different wavelengths, removing ambiguities in how spectral signatures map onto different parts of the accretion flow. In particular, strong X-ray emission lines from the extended jets strongly imply an outflow power that exceeds the radiative Eddington limit for reasonable compact object masses (see, e.g., Marshall et al. 2013). Of course, the mechanical luminosity is not governed by the radiative Eddington limit, but since the power in the jets is likely generated in part via accretion, it is possible that the mass accretion rate in SS 433 is super-Eddington.

It has recently been suggested that V4641 Sgr may be a precessing micro-blazar that launches extreme jets, based on an unusual *Chandra* X-ray spectrum obtained at low luminosity (Gallo, Plotkin, & Jonker 2014). The spectrum shows a strange hump or break, near to and above 4 keV. It may require a combination of relativistically-shifted emission lines from jets, as in the case of SS 433, and/or unusual continuum emission also tied to the jets. It is notable that the feature(s) detected in V4641 Sgr are far stronger than lines detected in SS 433.

However, in any high-mass X-ray binary (HMXB), the massive companion wind may serve to complicate inferences regarding the accretion flow. Such winds can be clumpy, and can give rise to aperiodic obscuration that may fully or partially cover the central engine (the well-known dips in Cygnus X-1 are one prominent example of clumps; see e.g. Hanke

et al. 2009). Such obscuration has been observed on multiple occasions in the spectrum of V4641 Sgr in both optical and X-ray wavelengths (Maitra & Bailyn 2006; Charles et al. 1999; Revnivtsev et al. 2002b). Even in the absence of clumps, shocks and ionization fronts can lead to an inhomogeneous medium (see, e.g., Watanabe et al. 2006).

When the direct continuum is wholly or partly blocked in a HMXB, the equivalent width of emission lines (arising via irradiation of the wind) can become very large (even 1–2 keV or more; see White, Nagase, & Parmar 1995). The full complexity of HMXB winds has become clear in the era of advanced CCDs and dispersive X-ray spectrometers (see, e.g., Torrejon et al. 2010). In Vela X-1, which harbors a B-type star (albeit one with a stronger wind than V4641 Sgr), excellent X-ray spectra and complex wind models have been compared; a wind with multiple zones, shocks, and columns that can approach $N_H \geq 10^{23} \text{ cm}^{-2}$ is clearly indicated (Watanabe et al. 2006).

V4641 Sgr is highly unusual even among HMXBs, and unique in other respects. The system harbors a black hole ($M_{\text{BH}} = 9.6^{+2.1}_{-0.9} M_{\odot}$) accreting from a high-mass B9 III-type ($M_{\text{C}} = 6.5^{+1.6}_{-1.0} M_{\odot}$) companion star (Orosz et al. 2001, although MacDonald et al. 2014 find slightly lower component masses: $M_{\text{BH}} = 6.4 \pm 0.6 M_{\odot}$ and $M_{\text{C}} = 2.9 \pm 0.4 M_{\odot}$). However, the inclination angle of the superluminal jet detected in 1999 by Hjellming et al. (2000) is likely $i_{\text{jet}} \leq 10^\circ$, whereas the inclination of the binary system is likely much higher, $60^\circ < i_{\text{binary}} < 70^\circ$ (Orosz et al. 2001). It is not clear how this geometry might affect observed spectra.

In this work, we examine *Chandra* observations of V4641 Sgr at low Eddington fractions, originally analyzed by Gallo, Plotkin, & Jonker (2014). We suggest an alternative explanation for the SS 433-like features that may be present in the spectrum. The observations and data reduction are described in Section 2. In Section 3, we report the results of our analysis. Finally we discuss our results in section 4.

2. OBSERVATIONS AND DATA REDUCTION

The data we utilize are archived *Chandra* observations performed in 2004 as the source was declining into a quiescent state. V4641 Sgr was observed at low flux in observations 4451 (start time: MJD 53203.45, duration: 9.2 ks), 4452 (start time: MJD 53216.76, duration 18.3 ks), and 4453

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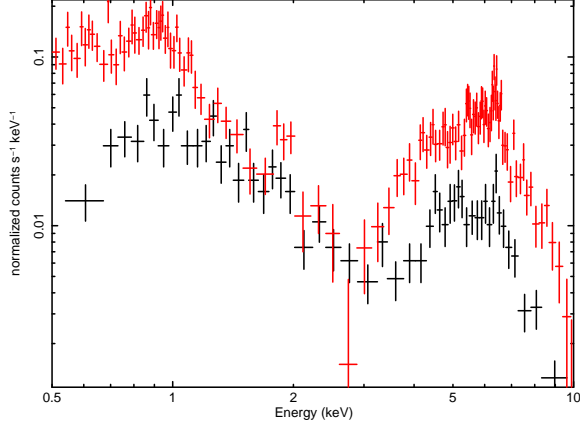


FIG. 1.— The figure above shows the *Chandra* spectrum of V4641 Sgr (in black), and a 2007 *XMM-Newton* observation of the well-known Seyfert-2 NGC 7582 (in red). Both spectra were binned to require at least 15 counts per bin; the spectrum of NGC 7582 was further binned for visual clarity only. No spectral fitting has been performed, nor has any flux scaling. Features consistent with a partial-covering absorption plus distant reflection geometry are evident in both spectra, and dominate differences between the *Chandra* and *XMM-Newton* area functions.

(MJD 53227.18, duration: 36.5 ks), using the ACIS-S detector. The CCD was operated in “FAINT” mode using a sub-array to prevent photon pile-up distortions. CIAO version 4.4 in the most up-to-date calibration files were used to reduce the “evt2” files. Using the “specextract” script, source and background spectra and responses were created from each observation. The source spectra were extracted using a circle centered on the source, with a radius of 10 pixels (4.92 arcseconds). Background spectra were extracted from an adjacent, source-free region of the same size.

The HEASARC/FTOOLS suite was used to further process the data. The familiar “grppha” was used to group all spectra to require 15 counts per bin, in order to ensure the validity of χ^2 statistics (cash 1979). The spectra were subsequently analyzed using XSPEC version 12.8.0 (Arnaud 1996). Models were fitted over the 0.5–8.0 keV energy range.

To facilitate a comparison with V4641 Sgr, we downloaded the 2007 *XMM-Newton* observation of the well-known Seyfert-2 NGC 7582 (observation 0405380701; see Bianchi et al. 2009). The XMM data were reduced using SAS version 13.0. Potential background flares were excised by analyzing the light curve of a background region on the same chip as the source. Standard filtering was performed (e.g. PATTERN ≤ 4 and FLAG = 0). Source and background spectra were extracted from circles with 30 arc-second radii, and corresponding response files were made using “rmfgen” and “arfgen”. The net exposure time after processing was 15.1 ksec. The spectra were grouped using the FTOOL “grppha” to require at least 15 counts per bin, as was done for the *Chandra* spectra of V4641 Sgr.

3. ANALYSIS & RESULTS

Figure 1 shows the *Chandra* spectrum of observation 4451 plotted with the *XMM-Newton* spectrum of the Seyfert-2 NGC 7582. The similarities between the two spectra are clear. Typical of Seyfert-2 AGN, Bianchi et al. (2009) find that the spectrum of NGC 7582 is fitted acceptably by a combination of strong and complex absorption, and distant reflection. In view of the spectral similarities between V4641 Sgr and NGC 7582, we constructed the following model: $tbabs \times pcfabs \times pexmon$ (Wilms, Allen & McCray 2000,

Nandra et al. 2007). The use of a single “pcfabs” component represents a simplified version of the multiple-component absorption and/or partial-covering absorption typically required to fit Seyfert-2 X-ray spectra (e.g. Turner et al. 1997; Matt et al. 2000; Risaliti, Elvis, & Nicastro 2002). “Pexmon” self-consistently generates Fe K emission lines and reflection features.

Within “pexmon”, an inclination $i = 0^\circ$ was fixed (however we find that the quality of the fit is insensitive to the inclination and similar values of the other parameters are returned when the binary inclination of 70° is used), and the abundance of elements heavier than Helium equivalent to the solar abundance (apart from iron, where an abundance $A_{\text{Fe}} = 0.3A_{\text{Fe,solar}}$ was fixed; fits are only slightly worse with a solar iron abundance: $\chi^2_\nu = 0.82$ as opposed to $\chi^2_\nu = 0.77$). The cutoff energy (E_c) was fixed at 10^6 keV. The other five parameters; the photon index (Γ), the scaling factor for reflection (f_{refl}), the normalization (K), the internal Hydrogen column density N_H , and its covering fraction f_{cov} were allowed to vary. The Galactic equivalent neutral hydrogen column density was fixed to $N_H = 0.18 \times 10^{22}$ atoms cm^{-2} (Kalberla et al. 2005).

The data and corresponding models are plotted in Figure 2, and the results are listed in Table 1. For observation 4451, the internal column is measured to be $N_H = 4.8(4) \times 10^{23} \text{ cm}^{-2}$, commensurate with some columns within Seyfert-2 AGN (e.g. Matt et al. 2000; Risaliti, Elvis, & Nicastro 2002), and short of being Compton-thick. Because much of the incident spectrum is obscured, the reflection fraction is found to be much higher than unity; indeed, as per Seyfert-2 spectra, it is reflection-dominated. An important outcome of this spectral model is that a fairly typical incident power-law index is recovered: $\Gamma = 1.96(8)$. Both this model, and the model proposed by Gallo, Plotkin, & Jonker (2014), achieve excellent fits ($\chi^2/\nu \leq 1$); the models cannot be distinguished on statistical grounds using these data.

The second and third spectra in the sequence, observations 4452 and 4453, do not require any absorption beyond the Galactic column, nor do they require significant reflection. They are well described with a simple power-law model, typical of black holes at low Eddington fraction. Apart from the lack of an absorbing column, these two observations differ from the first in several other respects. The power-law index is softer in the first observation ($\Gamma \approx 1.96$, see Table 1). Moreover, the unabsorbed flux in observation 4451 is a factor $\gtrsim 50$ higher than in observations 4452 and 4453. In tandem, then, these facts suggest a degree of continuum evolution as the outburst declined to a quiescent flux level.

4. DISCUSSION

We have reanalyzed three archival *Chandra* spectra of V4641 Sgr, obtained as the source declined into a quiescent state. The first spectrum in the sequence (observation 4451; see Table 1 and Figures 1 and 2) is of particular interest, as it shows strong deviations from a simple power-law. This spectrum is very similar to those commonly obtained from Seyfert-2 AGN (e.g. Turner et al. 1997; Matt et al. 2000; Risaliti, Elvis, & Nicastro 2002; Bianchi et al. 2009). When fit with a model based on Seyfert-2 spectra – one including partial covering absorption and distant reflection – an excellent fit is obtained, and a typical incident spectrum is recovered. In this section, we examine ways by which this spectrum

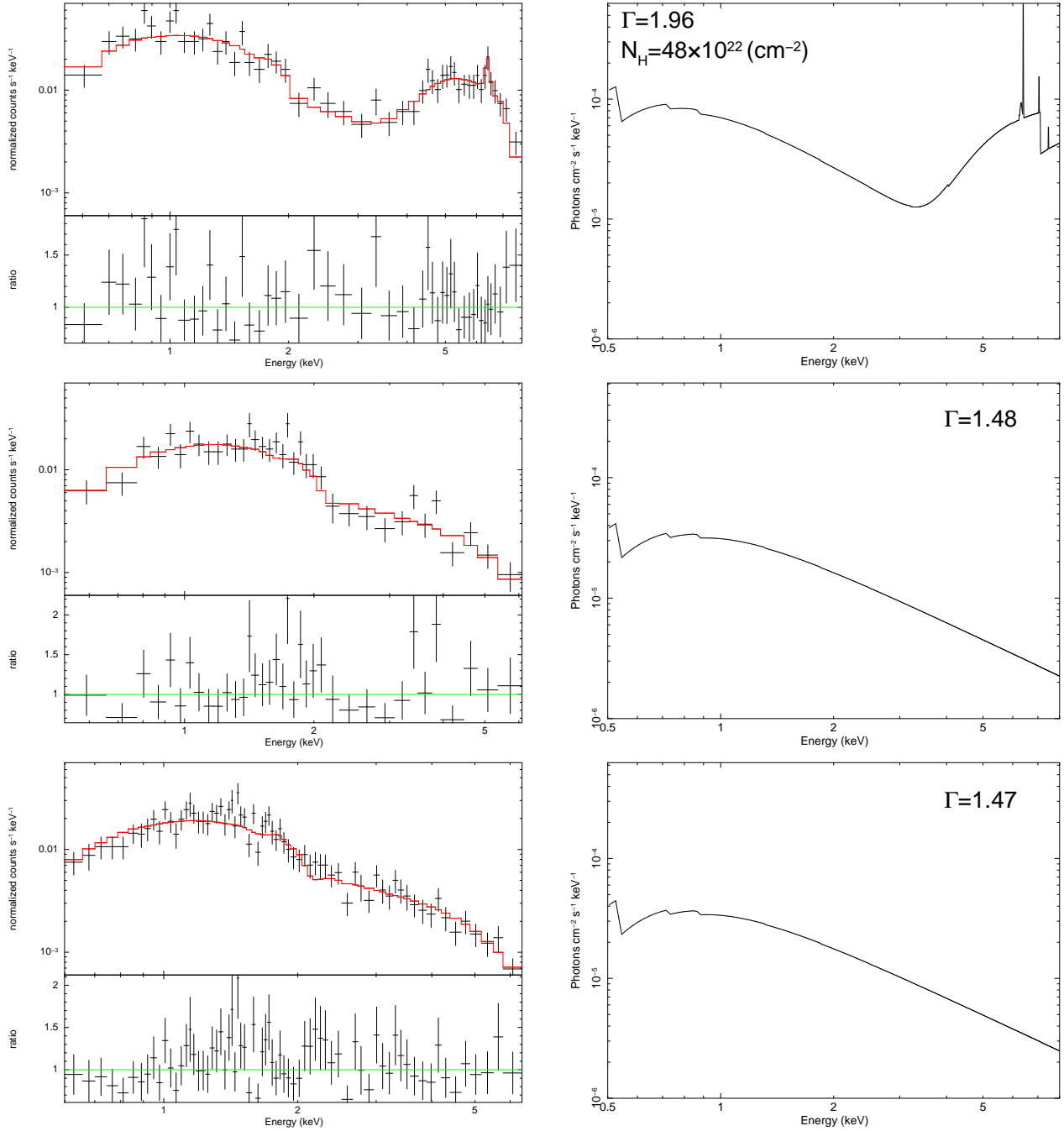


FIG. 2.— (Top) Data and model of observation 4451. (Middle) Data and model of observation 4452. (Bottom) Data and model of observation 4453. The data are on the left, and the models are on the right. Plotted below the data are the data to model ratios.

might arise in V4641 Sgr, implications for accretion flows onto black holes, and means of testing this model.

As briefly mentioned above, V4641 Sgr is not a standard X-ray binary. It is the only transient high mass X-ray binary with a dynamically-confirmed black hole primary (Orosz et al. 2001). Our expectations of high mass X-ray binaries harboring black holes are built upon persistent (but variable) sources such as Cygnus X-1, LMC X-1, and LMC X-3. The phenomena possible when black holes enter and return to quiescence in the presence of a high-mass companion are unexplored apart from V4641 Sgr. Although the companion wind in V4641 Sgr is likely to be weaker than in a source

like Vela X-1, accretion-induced changes in photoionization and shocks in a companion wind may cause inhomogeneities within it, and could lead to a complex absorption geometry (see, e.g., Watanabe et al. 2006). Of course, if the wind is clumpy, then a complex absorption geometry would also be likely.

Recently MacDonald et al. (2014) revisited the orbital parameters of V4641 Sgr by examining photometric data obtained over the last decade. They found that the companion star to V4641 Sgr exists in two states: a “passive” state in which the secondary exhibits very little intrinsic variability and the variations in the optical light curve are caused by the

TABLE 1
CHANDRA OBSERVATIONS OF V4641 SGR: BEST-FIT SPECTRAL PARAMETERS

Observation	MJD	ϕ	Γ	f_{refl}	K $\times 10^{-5}$	N_H 10^{22} cm^{-2}	f_{cov}	$\log L/L_{Edd}$	χ^2 (DOF)
4451	53203.45	0.97 ± 0.01	1.96 ± 0.08	$3.7^{+1.4}_{-1.2}$	390 ± 20	48 ± 4	$0.97^{+0.01}_{-0.02}$	-3.7	37.27 (47)
4452	53216.76	0.69 ± 0.01	$1.48^{+0.19}_{-0.12}$	0.0002^{+6}_{-3}	4.9 ± 0.5	—	—	-5.5	38.32 (34)
4453	53227.18	0.39 ± 0.01	$1.47^{+0.09}_{-0.08}$	0.0001^{+2}_{-1}	5.3 ± 0.3	—	—	-5.4	65.76 (68)

NOTE. — Parameters of V4641 found for the observations in our sample. Columns 3-9 are the best fit spectral parameters found using the model $tbabs \times pcfabs \times pexmon$. For observations 4452 and 4453, $pcfabs$ was not included in the model. The uncertainties are the 90% statistical uncertainty calculated using the “error” command in XSPEC. The Eddington fractions were estimated from the total unabsorbed flux between 0.5-8.0 keV, and assuming $M = 9.6 M_\odot$ and $d = 9.6$ kpc. The phases (ϕ) were calculated using $T_0 = \text{HJD } 2447707.4865 \pm 0.0038$ and $P_{orb} = 2.81730 \pm 0.00001$ days (Orosz et al. 2001).

orbital modulation, and an “active” state, in which variability in the light curve is dominated by the intrinsic variability in the secondary. Based on MacDonald et al. (2014) and prior work by Orosz et al. (2001), we find that observation 4451 occurs during the active state of the secondary, and observations 4452 and 4453 occur in the passive state. That observations 4452 and 4453 are so different from observation 4451 suggests that the peculiar spectrum may be partially caused by the increased/changed wind geometry etc. from the secondary. An active X-ray state combined with an active companion (wind) state could cause the shocks and fronts that would give rise to the observed spectrum, aided or unaided by clumps.

In a study of Seyfert galaxies, Akylas & Georgantopoulos (2009) found that the lower luminosity sources more often had unabsorbed nuclei, while the higher luminosity sources often had internal hydrogen column densities as high as $\approx 10^{24} \text{ cm}^{-2}$. The unabsorbed sources had Eddington-scaled luminosities comparable to observations 4452 and 4453, while observation 4451 had an Eddington-scaled luminosity closer to that of the obscured sources. That fact that the absorption behavior observed in V4641 Sgr seems to mirror Seyfert behavior may simply be coincidence. However, it could represent a physical similarity. One possibility may be a clumpy wind from the accretion flow operates at the Eddington fraction of observation 4451, but disappears at lower luminosity. Elitzur & Shlosman (2006) developed such a model for AGN.

V4641 Sgr is also unique in the degree by which the inner accretion disk appears to be misaligned with the binary system ($i \leq 10^\circ$ versus $i = 60-70^\circ$; Orosz et al. 2001). Depending on the vertical profile of the disk, the nature of the inner accretion flow, and how these geometries vary with the mass accretion rate, it is possible that the outer disk may act like the torus in AGN, and serve to partly or nearly entirely obscure the inner disk. This is another means by which a Seyfert-2-like geometry and spectrum might arise in V4641 Sgr; it is independent of the companion wind, but of course the two could act in concert.

In order to model the spectrum of observation 4451, prior efforts developed some jet-focused models, including extremely strong Doppler-split lines from SS-433-like jets and/or peculiar Comptonization (Gallo, Plotkin, & Jonker 2014). If the 4–8 keV spectrum is due to a set of lines, the lines are far stronger than those observed in SS 433 (e.g. Marshall et al. 2013), even though a far higher Eddington fraction would be estimated from SS 433 if it were viewed down its axis. Indeed, the jets in V4641 Sgr would have a bulk Lorentz factor of 15–45 (Gallo, Plotkin, & Jonker 2014).

While Lorentz factors this large are inferred in jets from supermassive black holes, they are considerably higher than the Lorentz factors typically observed in jets originating from other stellar mass black hole systems in the hard or quiescent states (see for example Fender, Belloni, & Gallo 2004). Moreover, the continuum implied in such fits is unusually hard, and inconsistent with standard Comptonization ($\Gamma = 0.93-1.07$), whereas our model recovers a more typical continuum.

It is possible that precessing jets have been observed in V4641 Sgr. However, in view of the qualitative and quantitative similarities between observation 4451 and well-known Seyfert-2 spectra, in view of the likely complexity of the environment in this transient, mis-aligned, high-mass X-ray binary, and in view of the fact that a canonical continuum can be recovered with an absorption plus reflection model, we suggest that the latter is also a compelling interpretation of the data.

One way to constrain the nature of the absorption is to examine the orbital geometry of the system at the times of our observations. In Cygnus X-1 at least, obscuration does appear to be phase-dependent. Any phase dependence may help to distinguish how the spectrum obtained in observation 4451 arose, so we calculated the phase (ϕ) of all three observations using orbital period and photometric T_0 calculated by Orosz et al. (2001; photometric T_0 is defined by Orosz et al. as the time of the superior conjunction of the secondary). The phases are listed in Table 1 along with the uncertainties estimated from uncertainties in their phase zero-point and orbital period. MacDonald et al. (2014) estimated a more recent T_0 using the same orbital period from Orosz et al. (2001). Folding our observations on that T_0 , the phase is comparable to that found by Orosz et al. Thus our choices of T_0 and P_{orb} (and, in turn, the phases we compute using them) are consistent with more recently performed studies of the secondary.

If we then accept these phase determinations, we find that observation 4451 occurs near phase 0.0 (i.e. when the black hole is closest to us). This nominally implies that the absorption may not be tied to an enhancement in the wind that is constant in binary phase, and suggests that the absorption is more closely tied to increased activity in the secondary and/or the inner accretion flow, and/or related effects on the outer accretion disk.

In summary, the unusual spectrum revealed in V4641 Sgr is similar to spectra obtained in Seyfert-2 AGN, and we suggest that a variety of plausible scenarios – some tied to the HMXB nature of V4641 Sgr, others to its odd system parameters – could produce the geometry consistent with a Seyfert-2-like spectral model. Other origins for the spectrum – including

X-ray line emission from extreme jets and/or Comptonization – cannot be ruled out, but we argue that partial-covering absorption and distant reflection provide a familiar explanation. Future observations that sample a declining X-ray flux trend in V4641 Sgr, and/or the orbital phase, may be able to better

reveal the nature of the spectrum.

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